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Title: Development of New Directions in Axion Dark Matter Searches

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Development of New Directions in Axion Dark Matter Searches

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The bright objects we observe in the night sky make up less than 20% of the matter in the Universe. More than 80% of matter is invisible dark matter [1], which was postulated because the amount of visible matter in galaxy clusters could not account for the galaxies' velocities [2]. Observations from cosmology and astrophysics that converge on the existence of dark matter include the cosmic microwave background power spectrum [3], cluster and galactic rotation curves [2], gravitational lensing [4,5] and large-scale structure formation [6]. The existence of dark matter is one of the biggest unsolved mysteries in physics, providing concrete evident for physics beyond the Standard Model (SM) of particle physics. Many particle candidates have been introduced, including weakly interacting massive particles (WIMPs) and ultralight bosons, such as the axion [7]. No candidates have been discovered, despite many searches, and the nature of dark matter is still unknown. The axion is a new fundamental spin-0 particle, which was originally motivated by explaining the strong charge-parity (*CP*) problem of quantum chromodynamics (QCD) [7], the theory of the strong nuclear force within nucleons. The *CP*-violating term in QCD within the SM is expected to generate a sizable neutron electric dipole moment (EDM), while the experimental upper bound is roughly one trillionth that size [8]. The strong *CP* problem is the non-observation of this neutron EDM. Discovery of axions would aid in understanding both the cosmological dark matter problem and the strong *CP* problem.

Detection of axions is challenging as they are very light and very weakly coupled to SM particles. Nevertheless, theorists have shown that axions can be detected via the axion-photon coupling which can convert axions into photons in the presence of a strong magnetic field. This has motivated the current axion-searching experiments such as the Axion Dark Matter eXperiment (ADMX) [9] and CERN Axion Solar Telescope (CAST) [10]. However, a new focus of research is exotic spin-dependent interactions associated with axions. We have recently developed a novel experimental approach to probe the axion-mediated exotic spin-dependent interactions [11]. Our approach aims to detect magnetic-fieldlike effects from the exotic spin-dependent interactions between fermions, using an extremely sensitive optically pumped magnetometer (OPM). The OPM is the most sensitive cryogen-free magnetic-field sensor reaching femto-Tesla sensitivity [12]. In this approach, the OPM serves as both a source of polarized electrons and a magnetic-field sensor, leading to a simple tabletop experimental design. The approach studies the exotic interactions between optically polarized electrons located inside an alkali vapor cell of an OPM and unpolarized or polarized particles from an external solid-state test mass, as shown in Fig. 1. A test mass brought close to an OPM can induce a new force if axions mediate the exotic interactions between the mass and the OPM.

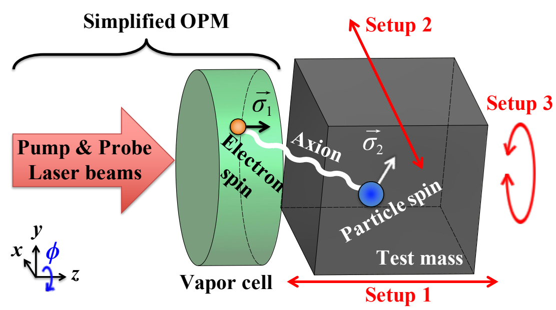

Fig. 1. Schematic of experimental setup to search for all fifteen axion-mediated spin-dependent interactions, using OPMs. There are three possible variations in the setup: the mass is reciprocally moved along the *z*-axis (Setup 1) and the *x*- or *y*-axes (Setup 2); it is rotated around the *z*-axis with a constant angular frequency (Setup 3).

There are 15 possible axion-mediated exotic interactions that contain static spin-dependent operators or both spin- and velocity-dependent operators [11]. Some of the interactions are not invariant under parity or time-reversal (*T*) symmetries; therefore, their observation would provide new sources for *P* and *T* symmetry violations, which are essential for the matter-antimatter asymmetry of the Universe that cannot be explained by the SM. Our approach has the great advantage of exploring all 15 exotic interactions. Recently, we investigated the spin- and velocity-dependent interaction between OPM polarized electrons and unpolarized nucleons, written as

$$V_{4+5} = \vec{\sigma} \cdot \vec{A} = -f_{4+5} \frac{\hbar^2}{8\pi m_e c} \hat{\sigma}_i \cdot \left[(\vec{\upsilon} \times \hat{r}) \left(\frac{1}{\lambda r} + \frac{1}{r^2} \right) e^{-r/\lambda} \right] \tag{1}$$

where $\hbar$ is Planck's constant, f is the coupling strength constant for the interaction, m_e is the mass of the spin polarized electron, c is the speed of light in vacuum, $\hat{\sigma}_i$ is the ith spin vector of the polarized electron with $\vec{\sigma}_i = \hbar \hat{\sigma}_i / 2$, $\hat{r} = \vec{r} / r$ is a unit vector in the direction between the polarized electrons and unpolarized nucleons, $\vec{\upsilon}$ is their relative velocity vector, $\lambda = h/m_a c$ is the interaction range (or the axion Compton wavelength), with m_a being the axion mass, and $\vec{A}$ is the axion field. The $\vec{\sigma} \cdot \vec{A}$ interaction is similar to that of a magnetic field $\vec{B}$ with the spin, $\vec{\sigma} \cdot \vec{B}$. In an OPM, an external magnetic field tilts the polarized electron spins by a small angle proportional to the field's strength, which is measured with a probe laser beam [12]. In our approach, the tilt produced by the axion field will be sensitively detected with a probe beam to determine or constrain the axion-mediated exotic spin-dependent interaction.

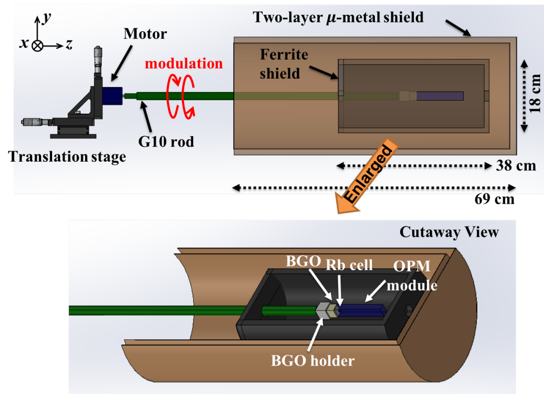

Fig. 2. Side view of a schematic of the experimental setup to probe the interaction V_{4+5}.

The experimental setup to probe the interaction V_{4+5} is shown in Fig. 2. For an unpolarized test mass, we used a 2×2×2 cm^3 cube-shaped non-magnetic bismuth germinate insulator [$Bi_4Ge_3O_{12}$ (BGO)] with high nucleon density of 10^{24} cm^{-3}. We used a cm-scale OPM with 15 fT/$Hz^{1/2}$ sensitivity from QuSpin Inc., that contains a 3×3×3 mm^3 ^{87}Rb vapor cell. The OPM was surrounded with ferrite and μ-metal nested magnetic shields to suppress the ambient magnetic noise. The Rb spins were polarized along the *y*-axis and the OPM was sensitive to the magnetic field in the *z* direction. To create the relative velocity term in the axion field, the BGO mass was rotated around the *z*-axis next to the Rb cell using a motor. In this configuration, only the component of $(\vec{v} \times \hat{r})_z$ remains, which tilts the Rb spins by a small angle. The tilt can be observed with the probe beam to nanoradian sensitivity. To suppress the systematic effects, mainly due to trace magnetic contamination of the BGO mass and the dc signal offset of the OPM, we compared the OPM signals between clockwise and counterclockwise mass rotations, because the systematic effects are the same for the opposite rotations while the sign of the axion signals is reversed due to only one velocity term in Eq. (1). For experiment details, see Ref. [13].

Figure 3 shows the experimentally set limit on the exotic interaction V_{4+5} between OPM polarized electrons and BGO unpolarized nucleons, free of systematic signals, in the axion mass of 10^{-6}–10^{-3} eV, corresponding to the interaction range of 10^{-1}–10^{-4} m. We experimentally constrained the interaction in this mass range for the first time, opening up new ranges of searches for axion-mediated exotic interactions. Unlike the axion experiments using cavities such as ADMX, the OPM can simultaneously scan the axion mass range without tuning parameters for each specific axion mass. Although no signal from axions for the interaction was detected, we plan to continue probing other possible axion-mediated exotic spin-dependent interactions. Very recently, we also experimentally constrained another spin- and velocity-dependent interaction between the OPM polarized electrons and the BGO unpolarized nucleons, V_{12+13} [16]. By linearly moving the BGO mass next to the Rb vapor cell, the experiment set the experimental limit in the axion mass of 10^{-6}–10^{-3} eV [16], improving the current limit by up to 17 orders of magnitude. These experiments shed light on the new direction of axion dark matter searches.

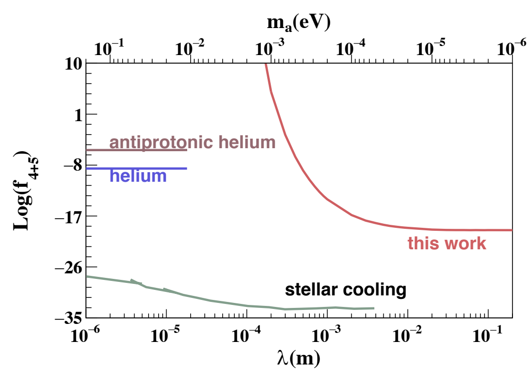

Fig. 3. Experimental limit on the coupling strength f_{4+5} of the exotic spin- and velocity-dependent interaction V_{4+5}: the red curve shows the experimental limit of this work on the interaction between polarized OPM electrons and unpolarized BGO nucleons as a function of the interaction range (bottom axis) and the axion mass (top axis) with the 82 h of data collection time. The coupling is the combination of the scalar electron coupling and the scalar nucleon coupling. The curve of stellar cooling combines the scalar electron coupling derived from stellar cooling and the scalar nucleon coupling derived from short-range gravity experiments. The figure also shows results from the measurement of helium fine-structure spectroscopy [14] of the scalar electron and scalar electron couplings and antiprotonic helium spectroscopy [15] of the scalar electron coupling and the scalar antiproton coupling.

We also proposed another OPM-based experimental approach to search for axion dark matter, that is sensitive in the axion mass range between 10^{-11} and 10^{-7} eV with a sensitivity that is four orders of magnitude beyond the current limit (for detail, see Ref. [17]).

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